



# Effect of particle size on microstructure and mechanical properties of composites produced by ARB process

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## ABSTRACT

In the present work, Al/10 vol.% SiC metal matrix composite (MMC) was manufactured by accumulative roll bonding (ARB) process. The silicon carbide particles with two various particle sizes of 40 and 2  $\mu\text{m}$  were used. Effect of particle size on microstructure (by scanning electron microscopy) and mechanical properties (tensile strength and elongation) at various ARB cycles was investigated. It was found that the microstructural evolution in MMC with 40  $\mu\text{m}$  particle size was more salient compared to the MMCs with 2  $\mu\text{m}$  particle size. Also, the composite strip with 40  $\mu\text{m}$  particle size became uniform with high bonding quality and without any porosity sooner than the strip of 2  $\mu\text{m}$  particle size. Moreover, when the number of cycles was increased, the tensile strength for both samples was improved. The tensile strength of the composite strip with 40  $\mu\text{m}$  particle size was more than the composite strip with 2  $\mu\text{m}$  up to the seventh cycle. By increasing the number of cycles after the seventh cycle, the value of tensile strength of MMC with 40  $\mu\text{m}$  particle size became saturated and then decreased, and its tensile strength became less than that of the composite with 2  $\mu\text{m}$  particle size for the ninth and eleventh cycles. Up to the seventh cycle, when the number of ARB cycles was increased, the elongation of composite strips was decreased, but after the ninth cycle, the tensile elongation for both samples was improved.

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## 1. Introduction

The attractive physical and mechanical properties that can be obtained with metal matrix composites (MMCs) such as high specific modulus, strength and thermal stability have been documented extensively [1–4]. The MMCs have higher strength in shear and compression and higher temperature capability because they are a combination of metallic properties (ductility and toughness) and ceramic properties (high strength and modulus). Interest in MMCs for aerospace, automobiles and other structural applications has grown over the last few years, as a result of availability of relatively inexpensive reinforcement as well as the development of new processing routes [1,3,4]. Although several processing methods have been developed to produce MMCs such as powder metallurgy and spray deposition, casting is the cost-effective one. In spite of that, cast aluminum alloy composites have serious problems for practical applications. The tensile ductility and fracture toughness at room temperature of the cast MMCs are significantly poor and their relatively high content of ceramic particulates makes them too hard. These problems encourage the establishment of new fabrication processes which can efficiently

produce engineering aluminum alloy composites [5]. Recently, present authors have developed accumulative roll bonding (ARB) [6–8] process and also invented a new technique, namely, continual annealing and roll-bonding (CAR) [9,10] process, in order to overcome the aforementioned problems. It should be noted that the ARB was invented by Saito et al. [11,12]. Accumulative roll bonding has been established as an effective means to fabricate ultrafine grained sheet metals by severe plastic deformation (SPD). Compared to other SPD techniques, such as equal channel angular extrusion and high pressure torsion, the ARB technique can be more easily scaled up for large production quantities of sheet metals [11,12].

The present authors [6–10] have reported much more improved microstructure and mechanical properties of MMCs by ARB and CAR processes. This improvement is associated with better particulate distribution and uniformity of the ARBed and CARed microstructures. However, the effect of particle size on microstructure and mechanical properties of produced composites has not been studied. Alizadeh and Paydar [13] have also fabricated the nanostructure Al/SiC composites by ARB process, but they have not investigated the effect of particle size.

Therefore, the aim of the present work is to produce Al/10 vol.% SiC MMCs by ARB process and investigate the effect of the silicon carbide size on the microstructure and mechanical properties of manufactured composites.

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## 2. Experimental procedure

The materials used in this study were fully annealed strips of AA1050 aluminum alloy and SiC particles with two different average sizes, 2 and 40  $\mu\text{m}$ . To produce a satisfactory metallurgical bond by the ARB process, it is essential to remove any contaminations that may be present on the surfaces of the metals to be joined. A number of authors have claimed degreasing followed by scratch brushing with a rotating steel brush to be the best method for surface preparation [14–19]. Therefore, two strips of 150 mm  $\times$  50 mm  $\times$  1.5 mm were degreased in acetone bath and scratch brushed with a stainless steel wire brush 0.26 mm in diameter. After surface preparation, SiC particles were uniformly dispersed between the two strips by a brush. In fact, in each cycle, the silicon carbide particles were weighed and added between the aluminum strips. Then the strips stacked over each other and fastened at both ends by steel wires. The roll bonding process was carried out with no lubrication, using a laboratory rolling mill, with a loading capacity of 20 tons. The roll bonding process was carried out with a specific amount of reduction equal to 50%. Then, the roll bonded strips were cut in half. The same procedure was repeated up to five cycles at room temperature (the first step). Then, to achieve a uniform distribution of reinforcement particles in the matrix and also to remove porosities in the interfaces of aluminum–silicon carbide and aluminum–aluminum, the above procedure was repeated again up to eleven cycles without adding reinforcement particles (the second step). The schematic illustration of the ARB process for manufacturing of composite is shown in our previous article [7].

PHILIPS XL30 scanning electron microscopy (SEM) was used for microstructural observation to evaluate how well the SiC particles were distributed in the produced composites at various ARB cycles. The tensile test samples were machined from the ARBed strips, according to the ASTM E8M standard, to get oriented along the rolling direction. The gauge width and length of the tensile test samples were 6 and 25 mm, respectively. The tensile tests were performed at room temperature on a Hounsfield H50KS testing machine at an initial strain rate of  $1.67 \times 10^{-4} \text{ s}^{-1}$ . The total elongation of the samples was determined as the difference between gauge lengths before and after testing.

## 3. Results and discussion

### 3.1. Microstructure observation

SEM micrographs of the microstructure for ARBed Al/10 vol.% SiC MMCs with various particle sizes (2 and 40  $\mu\text{m}$ ) after the fifth, seventh, ninth, and eleven cycles are presented in Fig. 1. After five cycles, it is clear that there are large particle free zones and agglomerated and clustered SiC particles in aluminum matrix (Fig. 1(a) and (b)). It is important that for particle size of 40  $\mu\text{m}$ , the particle free zones are larger, while the number of agglomerated or clustered particles is smaller than that of 2  $\mu\text{m}$  particle size. Generally, it can be said that the distribution of silicon carbide particles in aluminum matrix for both samples after the fifth cycle is completely non-uniform. Fig. 1(c) and (d) demonstrates that after the seventh cycle, the large particle free zones for 40  $\mu\text{m}$  particle size become smaller and the big number of agglomerated SiC for 2  $\mu\text{m}$  particle size becomes lower. On the other hand, the agglomeration and clustering of SiC for 40  $\mu\text{m}$  particle size and the size of particle free zones have not changed pronouncedly. Therefore, it should be said that the distribution of SiC particles for both samples after the seventh cycle becomes better, but it is still non-uniform. It can be seen from Fig. 1(e) and (f) that after the ninth cycle, the number of agglomerated and clustered SiC particles and the size

of particle free zones become again lower for both samples. But, it cannot be said that these microstructures are completely uniform. As the ARB process progressed forward and after the eleventh cycle (Fig. 1(g) and (h)), the clusters and the particle free zones almost disappeared. However, for the sample with 2  $\mu\text{m}$  particle size, there are still clustered silicon carbide particles in the aluminum matrix. In other words, unlike the samples with 40  $\mu\text{m}$  particle size, the microstructure of the MMC with 2  $\mu\text{m}$  particle size did not indicate a wholly uniform distribution of the SiC particles in the aluminum matrix after eleven cycles. Generally, it should be noted that the microstructural evolution in samples with 40  $\mu\text{m}$  particle size was more noticeable compared to the MMCs with 2  $\mu\text{m}$  particle size. In fact, MMC with 40  $\mu\text{m}$  particle size becomes uniform sooner than that with 2  $\mu\text{m}$  particle size.

Regarding the techniques used to establish atom-to-atom bonds between strip layers, it has been reported [3,14–21] that the film theory is to be a major mechanism in the roll bonding process. During roll bonding, two opposing brittle surface oxide layers produced after surface preparation break up coherently to expose the underlying metals which are extruded under normal roll pressure through widening cracks in the surface oxide layers from both sides of the interfaces. Also, during rolling, the metal plastically deforms and extends. In the presence of silicon carbide particles between the strips in the current investigation, the regions of SiC particles opened up into particles and, consequently, got uniformly distributed in the aluminum matrix. Furthermore, according to the film theory, aluminum flowed through the widening cracks in the surface oxide layers. The interface was, therefore, a combination of silicon carbide particles and bonded areas of extruded aluminum. Consequently, the opening of the surface oxide layer produced after surface preparation allowed for metal–metal contact and roll bonding to take place [6–10].

In addition to the uniformity of particles in matrix which was explained before, bonding quality between reinforcement and matrix and also porosity are other effective factors in the MMC properties. SEM micrographs of the composite strips after five, seven, nine, and eleven cycles at high magnification are shown in Fig. 2 for both particle sizes. From this figure, the bonding quality between silicon carbide particles and aluminum matrix and also porosity can be observed. For five and seven cycle ARBed samples, the bonding of the Al/SiC is very weak for particle sizes of 2 and 40  $\mu\text{m}$ . In the case of 2  $\mu\text{m}$  particle size, the porosity can be observed more in the clusters of SiC particles. From Fig. 2(e) and (f), it is obvious that unlike the MMC with 2  $\mu\text{m}$  particle size, the sample with 40  $\mu\text{m}$  particle size has a high bonding quality without any porosity in the matrix. However, when the number of ARB cycles increases again, the bonding becomes stronger and the porosity decreases so that after the eleventh cycle (Fig. 2(g) and (h)), there are no debonding and porosity in both composite strips. It can be suggested that the subsequent rolling improves the bonding of the Al/SiC interfaces introduced in the previous cycle and eliminates the porosity. In fact, the microstructure after eleven ARB cycles indicates a good bond since neither debonding nor porosity is observed. Therefore, it can be concluded that the bonding quality of the interface is very good by 50% thickness reduction in each cycle, which is considered very important in the ARB process.

It should be noted that the rolling process is advantageous over other metal forming processes such as extrusion. It has been reported [22,23] that the extrusion process can improve the microstructure of metal matrix composites. But, unlike the rolling process, the extrusion cannot eliminate porosity completely and can produce a high quality bonding between particles and matrix. In the extrusion process, hydrostatic compressive stresses exerted on the samples by reaction with die-walls assist in the closure of pores. While the rolling process involves two types of stresses at

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